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RHEOLOGICAL STUDIES RELATED TO INTERIOR BALLISTICS: A HISTORICAL PERSPECTIVE

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The model description of the solid-phase physics used within the XNOVAKTC code is derived and discussed. The rheological requirements of an interior ballistic code are elucidated. A chronologically ordered overview of the experimental research efforts to obtain rheological data is presented. Several published articles are examined in detail to provide the pertinent published rheological data of interest to interior ballistics in one location. The conclusions include a parametric tabular comparison of the principal experiments of the past 20 years.

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1. INTRODUCTION

Rheology is the study of a material's response under load. There are many methods used to determine a material's response characteristics, which include the Young's modulus, toughness, hardness, yield strength, resilience, and others which compose the mechanical properties of the material. Usually these properties are obtained using tensile machines, impact devices, and hydrostatic devices, as opposed to a material's physical properties, such as the density, specific heat, conductivity, emissivity, expansivity, physical structure, composition, etc., which are obtained through a plethora of other testing procedures.

Typically, a material investigated is to be used in a homogenous, continuous, and solid form, comprising part of a structure which must bear a load. This requirement results in a standard test in which a piece of the material machined to close tolerances is placed in a universal testing machine and pulled or compressed until failure occurs as hypothetically shown in Figure 1. The result of such a test produces the yield stress, the stress at which point a line initially parallel to the stress vs. strain curve, and placed at 0.2% offset, intersects the stress vs. strain curve. The integration of the stress vs. strain curve to this point is the modulus of resilience. The slope of the 0.2% offset line which intersects the stress-strain curve is the modulus of elasticity. Rupture of the material occurs after much more strain has been applied. The total integration of the stress vs. strain curve is the modulus of toughness.

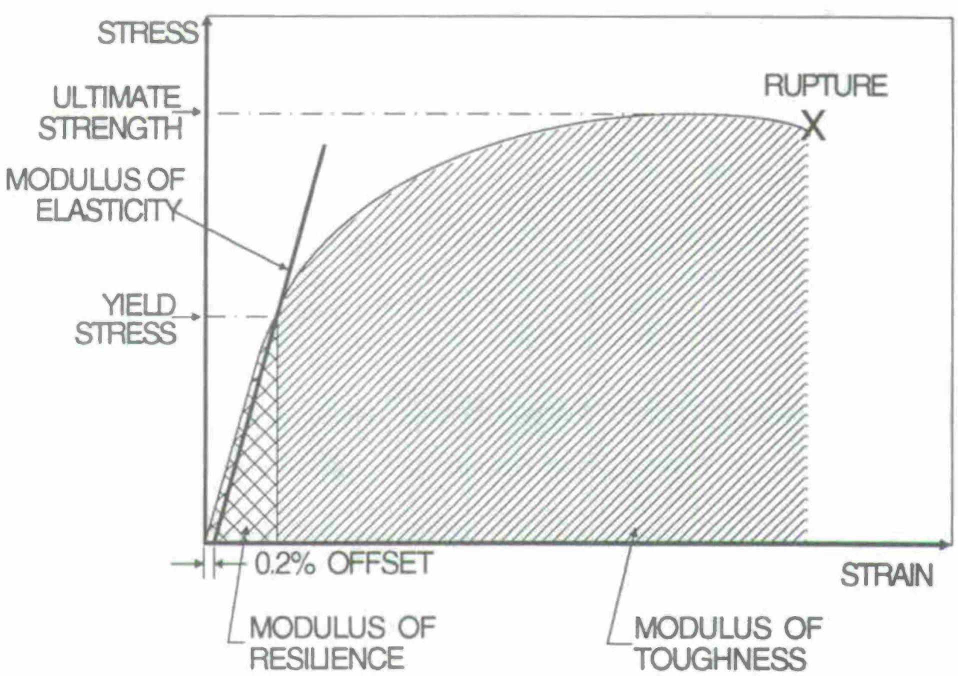

Figure 1. Hypothetical Material Response Curve.

Granular propellants and explosives are routinely subjected to loads ranging up to and over 1,000 atm. This report documents the efforts of previous investigators to determine the mechanical properties of these materials as they pertain to the interior ballistics of guns.

2. SOLID-PHASE COMPACTION FORMULATION OF THE XNOVAKTC CODE (Gough 1990)

XKTC is the latest version in a series of one-dimensional (with area change), two-phase flow interior ballistic (IB) codes written by Gough (1990). The balance equations describe the evolution of macroscopic flow properties accompanying changes in mass, momentum, and energy, and arising out of interactions associated with combustion, interphase drag, and heat transfer. The state variables are to be thought of as averages of local microproperties, with the intractable details of the microflow related to the macroscopic variables by means of empirical correlations or other experimental data.

This section is intended to provide a basis for the need of experimental compaction studies and what type of data is required by an IB code. A more thorough description of this formulation is to be presented in a second BRL report (currently under review) entitled "Rheological Formulation of the NOVA Family of Interior Ballistic Codes."

The averaged solid-phase incompressible momentum equation is given by Gough (1974) as

$$\varepsilon_s \rho_s \frac{D\vec{u}_s}{Dt} + \varepsilon_s \nabla p_g + \nabla\left(\varepsilon_s R\right) = \vec{f} \ .$$

The solid-phase continuity equation is presented as

$$\rho_s \frac{\partial \varepsilon_s}{\partial t} + \rho_s \nabla \cdot (\varepsilon_s \vec{u}_s) = \dot{m} \ ,$$

where ε_s, f, R, u_s, ρ_s, D, and $\dot{m}$ are the solid-phase porosity, interphase drag forces, stress tensor (assumed to be a scaler), solid-phase velocity, solid-phase density, substantial derivative, and mass production, respectively.

The solid-phase system of equations may be formulated into a wave equation through the following steps. Let $G(\varepsilon_s)$ be a function such that

$$\nabla (\varepsilon_s R) = \nabla (\sigma_s) = G(\varepsilon_s) \nabla \varepsilon_s \ .$$

Assuming

(1) $\varepsilon_s(0) = \varepsilon_{so}$

(2) $\vec{f} = 0$, no fluids in the propellant bed

(3) $\vec{u}_s(0) = 0$, the propellant bed is initially at rest

(4) $\dot{m} = 0$, no mass production,

linearizes the momentum equation to

$$\varepsilon_{so}\,\rho_s \frac{\partial \vec{u}_s}{\partial t} + G_o(\varepsilon_{so})\,\nabla \varepsilon_g = 0$$

and the continuity equation to

$$\frac{\partial \varepsilon_s}{\partial t} = -\,\varepsilon_{so}\,\nabla \vec{u}_s \,.$$

Taking the derivative of the momentum equation with respect to time and substituting in the continuity equation results in the following wave equation for quasi-static compaction:

$$\frac{\partial^2 \vec{u}_s}{\partial t^2} + \frac{G_o(\varepsilon_{so})}{\rho_s} \nabla^2(\vec{u}_s) = 0 \,,$$

where the wave speed is given by

$$a_{so}^2 = -\,\frac{G_o\,(\varepsilon_{so})}{\rho_s} \,. \qquad (1)$$

The constitutive assumption, which defines the solid-phase stress tensor, is embedded into $G(\varepsilon_s)$ by specifying a functional dependence of the propagation speed, a, which is assigned for a system undergoing loading as

$$a = a_1 \frac{\varepsilon_{go}}{\varepsilon_g} \,,$$

and unloading as

$$a = a_2 ,$$

where the user-supplied constant a_1 represents the speed of propagation during compressive loading when the bed is at the settling porosity, ε_{go}, and the input constant a_2 represents the propagation speed during unloading from any state.

A functional dependence of $\sigma(\varepsilon_s)$ may be developed by integrating the following relationship,

$$-\frac{d\sigma_s}{d\varepsilon_s} = -G(\varepsilon_s) = \rho_s \left(a_1 \frac{\varepsilon_{go}}{\varepsilon_g}\right)^2 = \frac{d\sigma_s}{d\varepsilon_g} ,$$

from ε_g to ε_{go}, where ε_g is the current porosity and ε_{go} is the settling porosity. This relationship generates the loading function used within the XNOVAKTC IB code:

$$\sigma_s(\varepsilon_g) = \rho_s\, a_1^2\, \varepsilon_{go}^2 \left(\frac{1}{\varepsilon_g} - \frac{1}{\varepsilon_{go}}\right).$$

3. REVIEWED RHEOLOGY LITERATURE

An accurate description of the stress-porosity relationship is critical to the accuracy of the numerical computations. Although many researchers work in the field of rheology (as is shown in the Reference List of this report), the following review is a representative cross section of the experimenters and their experiments in compressing beds of reactive materials, either propellants or explosives.

Few purely theoretical studies exist in the field of bed compaction. The theoretical background studies that do exist began in the 1950s with Brandt's (1955) application of Hertz's (1881) theory for deformation of spherical objects in contact. Carroll and Holt (1972) developed a dynamic pore collapse model, which matched well with data from porous aluminum experiments. The series of work that Carroll and Holt referenced between the mid-1950s and the early 1970s was primarily used for blast transmission studies in rock, soil, and loam. Jacobs and Sandusky (1986) described the bed compaction process for ball

propellants by representing the bed as a mixture of cubic lattices. Work is also currently being performed modeling granular bed properties, using single grain information, at the BRL.

There have been only a few groups in the past 20 years that have worked on the reactive bed compaction problem and its related concerns. Possibly the first person to work in this area was Soper (1973) at the Naval Surface Weapons Center (NSWC), Dahlgren, VA. He performed analytical and experimental studies on the mechanics of reacting solids. The first experimental group to investigate this area as applied to IB modeling was Horst (1975, 1976) (Horst and Robbins 1977) at the Naval Ordnance Station (NOS), Indian Head, MD, where he designed a bed testing facility. He also applied Soper's experimental work to Gough's (1974) code before any other measurements were made. Joining this group later on were Birkett (1981) and Robbins (Robbins and Conroy 1991) at Indian Head. Nicolaides, Wiegand, and Pinto (1980, 1982) also performed primarily single-grain studies. Alkidas and Summerfield (Alkidas et al. 1976) followed up Kuo's (Kuo, Vichnevetsky, and Summerfield 1973) theoretical modeling with some experimental validation. Later, Kuo conducted experiments with his students Koo, Davis, and Coates (Kuo et al. 1976; Kuo 1976), and Moore and Yang (Kuo, Moore, and Yang 1979) at the Pennsylvania State University. The fourth group to investigate packed propellant beds is Lieb, Gazonas, et al. at BRL. Lieb (Lieb and Rocchio 1982) began by working with single propellant grain studies until later when he applied a drop weight testing device (Lieb 1987) to the bed problem. His work in propellant characterization has incorporated various techniques (Lieb 1989, 1991a, 1991b; Lieb, Fischer, and Hoffman 1989; Lieb and Rocchio 1983, 1984; Lieb, Devynck and Rocchio 1983). Gazonas' work at BRL has primarily concerned single-grain studies (Gazonas 1991a; Gazonas and Juhasz 1991; Gozonas, Hopkins, and Ford 1991). In Germany, Zimmermann et al. (1984, 1985, 1990) (Grumann 1989a, 1989b; Stephenson 1987) have also investigated the compaction process of granular propellants during an IB cycle.

A few other groups were working in parallel on a very similar investigation into mechanical properties for the Hazard Assessment of Rocket Propellants Program (HARP) throughout the 1980s. These were the groups of Sandusky (Sandusky, Bernecker, and Clairmont 1983; Sandusky et al. 1988), Bernecker (Bernecker, Sandusky, and Clairmont 1979), Elban (1984) (Elban et al. 1982; Elban and Chiarito 1986; Elban, Coyne, and Chiarito 1987), Coyne (Coyne and Elban 1983), and Campbell (Campbell, Elban, and Coyne 1988) centered at the NSWC, White Oak Laboratories, VA; the Costantino (1983, 1984) (Costantino and Ornellas 1984, 1987, to be published; Costantino et al. 1987; Costantino and Tao, to be

published) group at the Lawrence Livermore National Laboratory (LLNL), NM; and the Kooker (1987, 1988, 1990) (Kooker and Anderson 1985; Kooker and Costantino 1986) group at BRL.

This is only a small listing of the total number of publications in the area of reactive material compaction. The analytical work, although not specifically related to propellant bed compaction, described in some of these publications could be useful, as well as the experimental techniques used to physically characterize high explosives. Looking more closely at some of these investigations through the resulting publications can give insight to the problems encountered and possibly answer why some experimental assumptions were made and whether these were reasonable. The work will be studied chronologically. Only the portions of the publications relevant to interior ballistics will be examined.

3.1 The Soper Report (1973). This is an experimental report using the 5-in/38 Naval gun to investigate ignition-induced pressure wave phenomena leading to projectile malfunction. A description of the experiment states that pressure gauges were positioned on the base of the projectile in the gun and at two points along the wall.

A second x-ray experiment utilized a spun-wound fiberglass chamber to gain visualization of the early ignition events. A third experiment consisted of a heavy-walled, steel cylinder in which propellant was placed and loaded to 65% of the theoretical maximum density (TMD). The result of that experiment provided a bulk modulus which was then used with Equation 1 to derive a wave speed in compression for NACO propellant of 441 m/s (1,450 ft/s). The bulk modulus under unloading conditions was about ten times that of the modulus under loading conditions; thus, the unloading rate was estimated to be about three times that of the loading rate.

3.2 The Horst Report (1975). This publication is the first in a series of reports detailing the advances of interior ballistic modeling during the 1970s, primarily concerning the NOVA code development up to the time of publication.

The NOVA code formulation presented in the 1975 report was derived from a control volume approach, and the formal averaging procedure results were also presented. The input data for the NOVA code, at the time of the 1975 report, incorporated the rheology properties in a bulk modulus or a wave speed input along with the settling porosity. Two particle stress laws were presented representing the functional dependence of stress on porosity in the bilinear form

$$R(\varepsilon_g) = 0, \qquad \varepsilon_g > \varepsilon_{go}$$
$$= \rho_s a_1^2 (\varepsilon_{g_o} - \varepsilon_g), \qquad \varepsilon_g \le \varepsilon_{go}$$

and analytical form

$$(1-\varepsilon_g) R(\varepsilon_g) = \rho_s a_2^2 e^{-\left(\frac{a_1}{a_2}\right)^2 (\varepsilon_g - \varepsilon_{go})} \quad , \qquad \varepsilon_g > \varepsilon_{go}$$
$$= \rho_s a_2^2 + \rho_s a_1^2 (\varepsilon_{go} - \varepsilon_g) \quad , \qquad \varepsilon_g \le \varepsilon_{go} \ ,$$

where

$$a^2 = \frac{-1}{\rho_s} \frac{d}{d\varepsilon_g}\left[(1 - \varepsilon_g) R(\varepsilon_g)\right]$$

and a_1 and a_2 are loading and unloading wave speeds in the bed, respectively. Relationships of this type were necessary for closure of Gough's relationship $a = a_1\varepsilon_{go}/\varepsilon_g$ to formulate the stress tensor in the solid-phase momentum equation. The experimental data for the wave speed at this time came from the Soper (1973) investigation.

3.3 The Horst Report (1976). This 1976 report documents the upgrades to the NOVA code which included descriptions of inert propellant components (wads or plugs), heat transfer to the gun tube, mixtures of propellants, and a gas permeable boundary (permeable breech or poor obturator). The report also details experimental data acquisition specifically tailored to provide input to the NOVA code, which included propellant thermochemistry data, primer discharge characteristics, and inert components' physical properties. It also includes efforts to establish the convergence of the numeric scheme with the experimental input. A κ attenuation factor for the propagation speed is introduced. This factor is used as an exponent to control the decay of the propagation speed to 0 as the gas porosity goes to 1.0, even though the bed is fluidized as opposed to the previous report where $R(\varepsilon_g) = 0$ for $\varepsilon_g > \varepsilon_{g_o}$. This decay behavior was introduced for numerical stability in the momentum equation. In the conclusions of the 1976 Horst report, it is noted that the physical response of the propellant bed to an intergranular stress wave could be important in the modeling of pressure wave phenomena in the gun chamber environment. Future work includes investigation into this area and the development of appropriate constitutive relationships for inclusion into the model.

3.4 <u>The Horst and Robbins Report (1977)</u>. This 1977 report includes modifications to the intergranular stress model to make it irreversible, thus eliminating the attenuation factor. The report also includes the following representation allowing for stick as well as granular propellants:

$$\frac{D\sigma}{Dt} = -\rho_s a^2 \left[\xi_6 + (1-\varepsilon_g)\frac{\partial u_s}{\partial x}\right],$$

where D/Dt_p is the convective derivative along the particle path line and $\xi_6 = \xi_2/\rho_s$ for granular propellant,

$$\xi_6 = \frac{\xi_2 \sigma_s}{(1 - \varepsilon_g)\rho_s^2 a^2}$$

for cord propellant, and ξ_2 is the source term of the continuity equation.

Experimentally, the report includes the description of the Navy's rheological test facility for propellant at NOS. An important finding with this device is that little rate dependence was observed over the cross head speed range of 0.254–50.8 cm/s. The resulting propagation rate data are given in Table 1. These data were obtained by applying the relation

$$a = \sqrt{\frac{1}{\rho_s}\frac{d\sigma_s}{d\varepsilon_s}} \qquad (2)$$

over some points in the early portion of the data.

A graph of the pressure difference profiles for the 5-in/54-caliber gun is then presented, showing the different results between the older reversible law and the newer irreversible relationship with various propagation speeds for input. The irreversible relationship using an unloading and loading hysteresis displays much stronger damping after the initial negative pressure difference than that of the reversible law.

3.5 <u>The Bernecker, Sandusky, and Clairmont Report (1979)</u>. This publication was the first in a series resulting from an increased interest in the solid-phase behavior of granular propellants, which resulted in a similar path of studies. An interesting point in this report is that a predetonation front whose velocity

Table 1. Horst Experimental Rheology Data

Propellant	Speed of Propagation (m/s)
NOSOL	88.90
NACO	306.68
M6	345.44
NACO (Soper)	441.96

is about 330 m/s had been recognized during the nitrocellulose experiments. This result is very close to the values reported by Horst for the speed of sound propagation in a bed. The reported speed of sound in the homogeneous double-based ball propellant material sample is 1,770 m/s.

The propellants evaluated in this work included two (obsolete) friable, cross-linked, double-based (XLDB) propellants (VLU and VLZ), a modified double-based propellant (FKM), and a nitrocellulose (NC) ball powder. The physical nature of the propellant material used to construct the porous charges varied. The FKM and NC were in a powdered form, the VLZ was shredded, while the VLU particles were cuboid. All of these materials had undergone a transition to detonation in a highly confined (steel tube) arrangement at comparable porosities in earlier work. The test results are given in Table 2 (the velocities are from flash radiography).

Table 2. Bernecker Visualization Test Data

Propellant	Density (g/cm^3)	TMD (%)	Propagation Speed (m/s)
Nitrocellulose	0.950	57.5	250.0
FKM (Granular)	1.000 1.000	54.6 100.0	260.0 1,770.0
VLU (Cuboid)	1.500	79.8	228.0
VLZ (Shredded)	1.100	58.2	236.0

3.6 The Kuo, Moore, and Yang Report (1979). This is Kuo's most recently published work which was to advance the understanding of propellant bed behavior. A review of previous correlations used by other researchers is given in the Introduction. An experiment was constructed to provide data with which to fit a correlation. The experimental test rig was constructed having two diametric piston heads. Displacement measurements were taken of the top piston head, which was moved using a Tinius Olsen machine quasi-statically. The applied and transmitted force was measured using strain gauges on the top piston and a linear displacement spring under the bed whose displacement was also recorded. A free body analysis of the test sample is presented, deducing the Newtonian equations for the internal and wall shear terms and the wall shear parameter relating the circumference to the shear times the contact perimeter.

The following empirical correlations were used with the constants given in Table 3 for the various propellants tested.

$$\overline{\left(\frac{\tau_{wp} P_{wp}}{\pi D}\right)}, \bar{T}_i = \left(\frac{R}{a}\right)^b, \qquad R \leq 0.216 \tag{3}$$

and

$$\overline{\left(\frac{\tau_{wp} P_{wp}}{\pi D}\right)}, \bar{T}_i = 1 + c\,\phi_o^d \left(\frac{R - a}{\phi_o^e - R}\right)^f, \qquad R > 0.216 \tag{4}$$

where ϕ is the gas phase porosity and R is the similarity parameter

$$R = \phi_o^e \sqrt{\frac{\phi_o - \phi}{\phi_o}} \; . \tag{5}$$

The experimental setup was modified at some later date to include dynamic loading of the propellant by means of a small-caliber projectile impacting the bed. However, these data were not uncovered by the author.

Table 3. Kuo Stress Correlation Constants

		a	b	c	d	e	f
WC-870	T_i	0.216	3.759	10.194	1.533	0.75	0.603
	$\tau_{wp}P_{wp}/\pi D$	0.216	1.829	8.210	1.800	0.75	0.921
WC-846	T_i	0.216	3.181	11.475	1.533	0.75	0.882
	$\tau_{wp}P_{wp}/\pi D$	0.216	1.568	12.314	1.795	0.75	1.225

3.7 The Scott Report (1978). This report summarizes the consolidated propellant experiments performed for the traveling charge concept. A dynamic combustion-driven piston experiment is described in detail. The test size was ~4 cm in diameter and 3 cm in length. Approximately 30 g of M1 propellant with a web size of 0.34 mm was compacted between two ram heads. A Kistler force gauge was located behind one of the ram heads. The other ram was combustion driven and had an extension rod which was used to determine location vs. time by reflecting the signal from a microwave interferometer.

This experiment was more for a proof of principle in constructing consolidated propellant samples than for obtaining rheological properties of various propellants. The resulting data consisted of the total charge weight, maximum load rate, average load rate to reach the maximum load rate, maximum load, maximum pressure in the driver chamber, and maximum strain of the propellant sample. The data, although expansive, were not presented in a form consistent with the other data in this report.

3.8 The Elban Report (1984). This is the first report produced by Elban specifically oriented toward the bed compaction project using the Farquhar press, which has a top force limit of ~2,670 kN. This report concerns beds of ball propellants at atmospheric pressure and low strain rates. Four Olin propellants were investigated—WC140, TS3660, Type A Fluid, and Winchester No. 231. The compaction device used was a Farquhar hydraulic press with a constant ram speed of 18.8 cm/min. The measurements taken were the applied force, transmitted force, and the top ram displacement.

Elban did not present his results as a single wave speed, but Kooker (1988) fitted the data to his empirical function where the derivative with respect to porosity is the bulk modulus, and thus produced propagation speeds at the settling porosities shown in Table 4.

Table 4. Wave Speed Calculation Performed on Elban's Data

Propellant	TMD Density (kg/m^3)	TMD (%)	Wave Speed[a] (m/s)
Winchester #231	1,640.0	50.0	105.1
TS3660	1,640.0	57.6	276.6
WC140 X3705	1,650.0	60.5	358.5
Type A Fluid	1,650.0	57.6	289.0

[a] Kooker (1988) calculation.

3.9 The Costantino Report (1984). This publication concerns the application of a hydrostatic loading device to two Hivelite® propellants (1086-8A and 1086-7B) used as a traveling charge in order to determine their state equations. The propellant samples were 18 mm in diameter by 40 mm long and vacuum-sealed. The samples were then loaded and unloaded twice hydrostatically to 200 MPa at a constant stress rate of 0.1 MPa/s to produce stress-strain curves. The propagation speeds of a small disturbance were then measured using ultrasonic time-of-flight during the hydrostatic compaction tests. These tests were performed at "fast" (10 MPa/min) and "slow" (10 MPa/30 min) loading rates. Both loading and unloading rates were obtained. The results of these measurements are presented in Table 5.

The compaction was characterized by three zones: (1) elastic region of the pore matrix, (2) failure region of the matrix and pores, and (3) compression of the failed material. The second compaction typically showed a less rigid initial response than the virgin material; however, the resulting compaction curve was, in general, much steeper after this initial response from that of the first loading curve. Constantino stated that the quasi-static experimental results may place an unwarranted burden on the numerical researchers, who must then incorporate rate dependence in their models. This technique was then applied to other energetic materials such as beds of HMX and JA2 single grains.

Table 5. Costantino Sound Speeds of Gun Propellants

	Slow Runs (10 MPa/30 min)				Fast Runs (10 MPa/min)			
	1086-8 A		1086-7 B		1086-8 A		1086-7 B	
P (MPa)	U_p (km/s)	U_s (km/s)	U_p (km/s)	U_s (km/s)	U_p (km/s)	U_s (km/s)	U_p (km/s)	U_s (km/s)
0.1	3.10	1.44	—	—	—	—	—	—
10	3.12	1.46	3.20	1.43	—	—	—	—
20	3.14	1.46	3.20	1.42	—	—	—	—
40	3.18	1.48	3.24	1.43	—	—	—	—
50	—	—	—	—	3.07 ±0.09	1.45 ±0.012	3.17 ±0.05	1.41 ±0.010
60	3.22	1.48	3.28	1.44	3.11 ±0.08	1.46 ±0.011	3.18 ±0.04	1.42 ±0.008
70	—	—	—	—	3.15 ±0.07	1.47 ±0.007	3.18 ±0.05	—
80	3.28	1.50	3.34	1.45	3.19 ±0.06	1.48 ±0.010	3.21 ±0.06	1.43 ±0.005
90	—	—	—	—	3.22 ±0.05	1.49 ±0.014	3.22 ±0.06	—
100	3.36	1.54	3.45	1.48	3.26 ±0.04	1.53 ±0.014	3.22 ±0.06	1.44 ±0.008
110	—	—	—	—	3.29 ±0.04	1.51 ±0.014	—	—
120	3.62	1.60	3.60	1.52	3.32 ±0.04	1.52 ±0.013	3.23 ±0.06	1.44 ±0.013
130	—	—	—	—	3.36 ±0.04	1.53 ±0.014	3.29	—
140	3.64	1.60	3.61	1.52	3.39 ±0.04	1.54 ±0.013	3.25 ±0.07	1.46 ±0.022
150	—	—	—	—	3.43 ±0.04	1.55 ±0.013	3.33	—
160	3.66	1.60	3.63	1.52	3.47 ±0.03	1.57 ±0.014	3.333 ±0.10	1.49 ±0.035
170	—	—	—	—	3.50 ±0.03	1.57 ±0.011	3.37	—
180	3.71	1.62	3.65	1.53	3.53 ±0.03	1.58 ±0.014	3.33 ±0.10	1.49 ±0.035
200	3.74	1.62	3.66	1.53	3.60 ±0.02	1.60 ±0.009	3.37 ±0.10	1.51 ±0.044

U_p - compression wave speed
U_s - shear wave speed

3.10 The Kooker and Anderson Report (1985). Kooker has performed extensive modeling work in the area of solid-phase wave motion in materials such as Hivelite® propellant, HMX, and others. Much of his efforts in the area of solid mechanics focuses on the constitutive modeling of the solid-phase equation of state for closure of the solid-phase momentum equation in his two-phase modeling.

During their work with Hivelite® propellant, Kooker and Anderson (1985) attempted to apply the pore collapse model of Carroll and Holt (1972) to the experimental data given by the Costantino group (1984). To obtain more accurate results, a modified version of Walton's (1977) soil mechanics model was applied,

$$P_{eq}(\alpha, e_c) = \left[\tau_o + (\tau_1 - \tau_o)\left[1 - \left(\frac{\phi}{\phi_o}\right)^{P_1} - \tau_2\left(1 - \left(\frac{\phi}{\phi_o}\right)^{-1}\right)\right]\right]\left[1 - \left(\frac{e_s - e_{so}}{e_{ml}}\right)^2\right]\ln\left(\frac{1}{\phi}\right), \qquad (6)$$

where ϕ is the gas phase porosity, P_{eq} is the equilibrium stress field in the solid phase, and e_s is the solid-phase energy. This relationship includes compressibility of the material. The plots presented in the report of the stress function (where overlayed on experimental data) show the potential of such a function in representing the data. Kooker points out that the percentage of TMD could go over 100% without the inclusion of compressibility. Kooker then goes on to develop a two-phase system of equations demonstrating the use of the constitutive relationship in the prediction of Hivelite® combustion.

Kooker and Costantino held a JANNAF workshop in 1986 and reported their results (Kooker and Anderson 1985; Kooker and Costantino 1986). Kooker used the constitutive relation (Equation 6) throughout his work (Kooker and Anderson 1985; Kooker and Constantino 1986; Kooker 1990) in his continued efforts to model the compaction wave behavior in energetic materials. This work came to an end in 1990 as the HARP program finished, and the problem appears to be well in hand at this time.

3.11 The Lieb Report (1987). After a great deal of work done by Lieb on more fundamental studies of homogeneous propellant response between the mid-1970s and mid-1980s, a new approach was applied to the bed compaction study. A drop weight test was performed on a bed roughly the same size as that used by Birkett (1981). This test was designed to increase the strain rates above those of the conventional quasi-static tests done heretofore. The test setup is essentially a piston inside a cylinder with a drop weight residing above the piston at a given distance. The quantities measured are the mass and height

of the drop weight and the force transmitted through the bed to a force gauge located in the center of the bed at the bottom. Three propellants were tested (M30, JA2, and XM39), at ambient temperature. The test results are given in Table 6. Sound speeds were computed from the stress-strain curves using the relation

$$C^2 = \frac{1}{\rho_s}\left(\tau_i - (1 - \varepsilon_g)\frac{d\tau_i}{d\varepsilon_g}\right),$$

where τ_i is the intergranular stress, and ε_g is the gas porosity.

Table 6. Lieb Drop Weight Test Results

Propellant	M30	JA2	XM39
Maximum Stress (MPa)	18.6 ±3.6	12.0 ±4.2	10.8 ±0.7
Stress at Failure (MPa)	14.5 ±2.4	7.4 ±3.7	8.0 ±0.7
Strain at Failure	2.8 ±0.3	2.5 ±0.4	2.0 ±0.2
Modulus (MPa)	505 ±150	366 ±154	558 ±43
Strain Rate (S^{-1})	56 ±3	53 ±3	56 ±7
Density (g/cm^3)	1.61	1.58	1.63
Bed Mass (g)	187.6	191.3	211.9
Slope[a] (MPa)	-1,305	-800	-777
Initial Porosity	0.456	0.436	0.391
Sound Speed[a] (m/s)	~665	~550	~550
Sound Speed[b] (m/s)	~400	—	~220

[a]Intragranular Stress < 10 MPa, below the slope break
[b]Intragranular Stress > 10 MPa, above the slope break

If one makes a calculation for time of flight using the signal delay between the first contact of the drop weight hitting the piston and that of the response of the force transducer placed below the bed and incorporating the length of the piston and its modulus, a solid-phase wave speed of 339 m/s is computed for initial tests of inert grains to characterize the drop weight device.

3.12 The Sandusky, Glancy, Campbell, Krall, Elban, and Coyne Report (1988). With the exceptions of Kuo's (Kuo, Moore, and Young 1979) projectile-driven bed, Lieb's (1987) drop weight test, Scott's (1980) report on consolidated propellant, and the work performed in Germany by Zimmermann (1985), there has been little investigation into the dynamic response of a compacted bed of energetic material. Probably this is due to the difficulties and exceedingly high cost of repeatedly producing a controlled high-force, high-rate compression test. This 1988 report documents both the dynamic and quasi-static tests performed by the White Oak group.

The quasi-static experiments of Elban's (1984) report were analyzed, and Kuo's intergranular stress (Kuo, Moore, and Young 1979) and Kuo's wall shear term were computed.

The dynamic experimental setup consisted of an energetic material used to propel a rod of known physical characteristics into a cylinder containing the test sample. Microwave interferometry was used to determine the velocity of the compaction wave. The two propellants studied were TS 3659 ball and WC-231 rolled ball. The test measurements and results are presented in Table 7.

Table 7. Sandusky Summary of Dynamic Loading Experiments of TS 3659 Ball Propellant Composition: 78.4% NC 21.6% NG

Shot PDC	TMD_o^a (%)	L^a (mm)	Tube[a]	V_p^a (m/s)	u^b (m/s)	U^b (m/s)	TMD^b (%)	P^b (MPa)	Δt^b (μs)
76	60.2	146.1	Lexan	~150	—	—	—	—	—
77	60.2	146.0	Lexan	~200	—	—	—	—	—
78	60.2	146.0	Lexan	291	207	—	—	—	83
80	60.2	101.7	Alum.	160	127	494	81.0	62.0	100
81	60.1	146.8	Steel	237	192	534	93.9	101.0	84–100
82	60.1	146.8	Steel	300	216	557	98.2	119.0	<80

[a]Initial conditions; [b]Results: $\%TMD_o$ = Initial bed density; $\%TMD_o{*}U/(U-u)$ = Jump condition calculation for bed compaction; L = Bed length including driven end disk (~0.8 mm); V_p = Velocity of Lexan piston just prior to bed impact; u = Particle velocity of bed (piston velocity after bed impact); U = Compaction front velocity; P = compaction pressure; Δt = Time between bed impact and detection of reaction.

The White Oak group has published many other papers concerning high explosive material research, which is indirectly related to the propellant bed rheology, and are listed in Section 5. The experiment, data acquisition, and reduction techniques performed by this group demonstrate what is practiced, feasible, and should be examined for future granular propellant tests.

3.13 <u>The Robbins and Conroy Report (1991)</u>. The reported test description given by Birkett (1981) produced a rather broad database for M30 propellant at three different temperatures. Experimental results converted into wave speeds are given in Table 8 using the standard wave speed equation (Equation 1). These data were analyzed using Gough's formulation, and an alternate correlation,

$$\sigma_s = \frac{-\rho_s a_1^2}{3}(\varepsilon_{go} - \varepsilon_g)^3 ,$$

was given to describe the stress-porosity relationship for the linear region of the cold and ambient experiments.

An exponential fit was performed to the equation

$$G = \frac{\sigma_0}{q_o} + \left(E(o) - \frac{\sigma_o}{q_o}\right)e^{\frac{-q_o}{q_1}t} ,$$

derived from a simple linear viscoelastic model. Comparisons of the equation and experimental data are more reasonable in the regions of almost pure elastic deformation of the bed than in the region of pore collapse and grain rearrangement.

3.14 <u>The Gazonas and Juhasz Report (1991)</u>. Gazonas has written a series of reports (Gazonas 1991a, 1991b; Gazonas and Juhasz 1991; Gazonas, Hopkins, and Ford 1991) concerning the importance of physical parameters upon the deformation and subsequent closed-bomb analysis of propellants. This particular report is the result of a study in which single grains of two propellants were tested uniaxially under various conditions including temperatures, aspect ratios, strain rates, and total strains.

Table 8. Robbins Rate of Propagation of Intragranular Stress a_1 at the Settling Porosity With Different Force Levels and Temperatures

Final Top Force (N)	-54° C a_1 Top (m/s)	-54° C a_1 Bottom (m/s)	12° C a_1 Top (m/s)	12° C a_1 Bottom (m/s)	63° C a_1 Top (m/s)	63° C a_1 Bottom (m/s)
16,200	253	216	166	138	85	65
	282	248	179	152	93	61
	247	211	185	119	—	—
20,800	—	—	190	167	—	—
	—	—	178	158	—	—
	—	—	182	158	—	—
26,700	—	—	176	155	—	—
31,100	239	208	187	160	101	67
	254	220	195	161	—	—
	—	—	182	163	—	—
	—	—	184	164	—	—
	—	—	189	159	—	—
48,900	251	208	186	161	105	77
	256	213	190	159	115	88
62,300	242	199	193	166	107	80
	224	188	190	167	120	95
	229	192	195	173	123	94
AVE.	248	210	185	157	106	78
S. D.	(16.1)	(16.8)	(7.5)	(12.6)	(13.1)	(13.2)

Note: These data were obtained with the Horst-designed test equipment at NOS.

The resulting propellant samples were placed after the compression test in a closed-bomb chamber and burned to determine the apparent burn rate. All these data were then statistically analyzed using the RS1 statistical package. The empirical response surface, Y, is given as

$$Y = b_o + \sum_{i=1}^{q} b_i X_i + \sum_{i=1}^{q} \sum_{j \geq i}^{q} b_{ij} X_i X_j \, ,$$

where the b_i coefficients are shown in Table 9.

Table 9. Gazonas Coefficients and Rankings for Predicting the Apparent Burn Rate (@20 MPa) of M30 and JA2 Propellants (Combined Analysis)

	Combined Analysis		JA2		M30	
Factor	Coefficient[a]	Rank	Coefficient	Rank	Coefficient	Rank
Propellant	0.2632	2	—	—	—	—
Strain Rate	–0.0151	9	–0.0998	5	0.0695	4
Strain	0.1940	4	0.4653	1	–0.0772	2
Temperature	–0.2311	3	–0.3792	2	–0.0830	1
Propellant * S.R.	–0.0846	7	—	—	—	—
Propellant * Strain	0.2712	1	—	—	—	—
Propellant * Temp	–0.1481	6	—	—	—	—
Strain Rate * Strain	–0.0031	10	–0.0667	6	0.0615	5
Strain Rate * Temp	–0.0762	8	–0.1452	4	–0.0073	6
Strain * Temp	–0.1904	5	–0.3087	3	–0.0720	3
Constant	2.3460	—	2.6090	—	2.0820	—
R-Squared (adj)	0.7150	—	0.7580	—	0.8610	—

[a]The coefficients ranked 1, 2, and 3 are significant at the alpha = 0.05 confidence level. Note also that strain and the interaction strain * temperature (rank numbers 4 and 5) are almost significant at the alpha = 0.05 confidence level.

The important finding of this study is that the strain rate is not a dominant factor in the production of additional surface areas between strain rates of 10^{-2} s^{-1} and 10^{+2} s^{-1} for either JA2 or M30; however, total strain is a rather strong factor. Gazonas intends to expand this work to higher strain rates (Gazonas 1991b) to see if the effect is still insignificant.

The consequence of this discovery is that the bed experiments may not need to be performed over a wide range of strain rates. This strengthens the results of a quasi-static experiment to provide data for use in higher strain rate scenarios. Thus, a very expensive high-force/high-strain rate universal testing machine may not be required.

3.15 The Lieb Report (1991a). This is the first publication of Lieb's work using an Instron universal testing machine applied to his drop weight testing fixture. The propellants tested were JA2, M30, XM39, and XM43. The strain rates applied were ~50/s (given the 4-cm-high bed which was 8.28 cm in diameter). All of the tests were performed at 295 K, with measurements taken of the applied, transmitted, and centralized (middle of the ramhead next to the propellant) loads. The resulting modulus is given in the report and is presented in Table 10 for both individual grains and bed response. From this information, the author computed the columns of the propagation speed in this material using Equation 2. These results show that strain rate effects may need to be investigated further.

Table 10. Lieb Quasistatic Bed Compaction Results

Prop.	ρ (kg/m^3)	Bed				Grain			
		G 50/s (MPa)	Wave Speed (m/s)	G 0.02/s (MPa)	Wave Speed (m/s)	G 50/s (MPa)	Wave Speed (m/s)	G 0.02/s (MPa)	Wave Speed (m/s)
JA2	1,580	366	481	9.33	77	770	698	190	347
M30	1,610	505	560	35.5	149	2,340	1,206	1,210	867
XM39	1,630	558	585	—	—	2,980	1,352	1,130	833
XM43	1,650	—	—	52.4	172	3,200	1,393	1,200[a]	853

[a]Projected from XM39 results.

Many other publications on propellant mechanical properties have been published by Lieb (1989, 1991b); (Lieb and Rocchio 1982, 1983, 1984; Lieb, Fischer, and Hoffman 1989; Lieb, Devynck, and Rocchio 1983). Principally, these are investigations of the homogeneous material or structural mechanics of individual propellant grains, in the continuing effort to understand the basic physical nature of propellants in order to ultimately make a link between single-grain properties to a multi-grain interaction through analytical modeling rather than through the use of a correlation.

3.16 Other Groups. Another group which has performed single-stick mechanical failure analysis which should be mentioned is the group of Nicolaides, Wiegand, and Pinto (1980, 1982) of the U.S. Army Armament, Research Development, and Engineering Center at Picatinny Arsenal, NJ. The studies which they performed using RDX triple-based propellants were very similar to Gazonas' experimental work.

A summary publication of the ongoing work in Germany by Zimmermann and his colleagues was obtained by the author when Zimmermann recently visited BRL in the spring of 1991. The publications referenced in the review are Zimmermann (1984, 1985, 1990), Grumann (1989), Grumann et al. (1989), and Stephenson (1987). The review describes various experiments ongoing in Germany at this time, including a combustion-driven piston propellant compaction experiment for dynamic testing, a drop weight experiment with a bed diameter of 5.5 cm and height of 10 cm, and a full-scale instrumented tank round simulator with a burst diaphragm instead of a projectile. Also, they have instrumented the base of projectiles to measure the local granular pressure on the base during firing. The data presented in the reports were not of the form given by the other authors. Their experimental designs should not be overlooked when a new experiment is designed.

4. CONCLUSIONS

This brief overview of what has been accomplished in the past has provided the reasons why the rheological properties of propellants are needed and how researchers in the past have attempted to obtain these properties. Typically, the technique used by the experimentalist was to compress a "bed" sample which was judged to be homogeneous in nature with respect to the grain size, initial porosity, temperature, and initial stress (if any). Primarily, in the gun propellant tests, the grain size with respect to that of the test specimen was considered. This consideration invariably led to a larger test bed diameter, which lowered the applied axial pressure to the bed. The smaller samples investigated by the high explosives group, as shown in Table 11, have very high-potential axial pressure levels, given their sometimes modest compressive machines. The largest machine applied to the test, Elban's Farquhar at 2,670 kN maximum load, was perhaps under-utilized considering the size of his test specimen. On the other hand, if such a machine were applied to the examination of a bed perhaps the size of a 155-mm howitzer or 8-in gun, then this would be an appropriate device to obtain the desired 100-MPa mixture stress which the NOVA code models under adverse simulated conditions. Table 11 provides a comparison of the experiments of the various groups testing granular material. Table 12 provides typical full-scale gun dimension data for comparison purposes. The measurements typically retrieved from the tests are:

Mixture density	- Linear displacement transducers.
Axial force	- Force gauge measurements. Top and bottom platen measurements are typically different due to the wall shear.

Table 11. Past Rheological Tests

Experimenter(s) (sample type)	Test Type	Test Measurements: force top	force bottom	wall shear	ram displacement	Test Dimensions L (cm)	D (cm)	Sample Dimensions L(cm), d(cm), web	Maximum Force (kN)	Test Area (cm^2)	Max Stress (MPa)
Horst Robbins Birkett (Granular Propellant)	quasi-static	yes	yes	yes	yes	~5.08	~7.77	2.436 1.072 .208 (M30)	~98	47.44	20.7
Kuo Moore Yang (Spherical Propellant)	quasi-static	no	yes	yes	yes	~3.937	~1.016	Dia = 0.0406 (Ball)	~5.4	12.17	4.43
	dynamic (.22 cal projectile)	results not obtained by author				—		—	—	—	—
Hercules (M1), (8567) (Granular Propellant)	dynamic	yes	yes	yes	yes (microwave inter-ferometer)	2.50	3.60	0.276 0.233 0.0258	>208,665	10.18	>205
Elban Sandusky Bernecker Clairmont Campbell Glancy (HMX),(TS3659), (WC231)	quasi-static	yes	yes	yes	yes	~1.52	2.54	#20 sieve cut (HMX)	2670	5.067	5,269
	dynamic (driven long rod)	no	no	yes measured σ_r	yes (microwave inter-ferometer)	~12.5	2.54	0.0434	~60. w/o RXN	5.067	~120
Costantino (HMX) & (liquid)	quasi-static	yes	no	none (hydrostatic compression)	yes	~1.905	~2.54	#20 sieve cut (HMX)	~27	5.067	53
Zimmermann Stephenson Grumann (M30), (JA2), (A5020), (15640)	drop weight	yes	yes	yes	yes	10.0	5.5	—	2 GPa/ms	23.76	4.2
	dynamic	yes	yes	yes	yes	3.0	5.0	—	>140.0	19.63	>71
Lieb (Granular Propellant) (CAB/ATEC/RDX) (JA2),(M30)	drop weight	no	yes	yes	yes	~4.0	8.29	1.38 .883 .183	~32.0	53.98	.747
	quasi-static	yes	yes	yes	yes	~4.0	8.29	1.491 .989 .184	~4.0	53.98	~6.0

Table 12. Typical Current Gun Systems Sizes

Gun System	Chamber Dimensions			Charge	Grain Dimensions			Comparison of Chamber/Grain
	Length (cm)	Rad@Breech (cm)	@Base (cm)		Length (cm)	Diameter (cm)	Web (cm)	(D/d)
8-in	106.680	10.777	10.262	JA2 19-perf	1.633	1.044	.132	19.95
155-mm	82.042	9.169	7.823	M30A1 7-perf	2.408	1.059	.201	16.04
120-mm	59.436	7.620	5.994	JA2 7-perf	1.633	1.054	.185	12.92

A question arises concerning all the previous tests: If a different force measurement is taken at top and bottom, then some of the strain energy must be accounted for through the radial force against the confirming cylinder and ultimately through the axial shear force at the cylindrical walls, which is typically supported in parallel to the lower force gauge. The radial force is then not measured nor considered by most, except for the White Oak group which has made substantial advances in this area. Indeed this group has obtained the radial deviator stress from many propellants and explosives (Coyne, Elban, and Campbell 1990) including Class D HMX, ABL 2523, WC 140, TS 3660, TS 3659, Winchester #231, and TS 3661. According to Robbins (Robbins and Conroy 1991), this radial force can be as high as 50% of the applied axial force. The hydrostatic stress state that Gough surmises, and that some of the tests were designed to represent, should probably be modified to include this radial component as well as the axial component of stress in some logical fashion.

In future tests to be conducted by BRL, we will attempt to eliminate the integrated wall shear force; the radial stress will be measured, as well as the standard ram displacement. Use of the resulting data is expected to require the combination of these components into some physically meaningful fashion to satisfy the requirements of the present versions of the interior ballistic codes. The data will be presented in a tabular form for each test and correlated to some function requiring fitting constants. These data will also be archived appropriately for any future computations.

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LIST OF SYMBOLS

D/d	=	Bed diameter/propellant grain size
G	=	Bed modulus
L	=	Bed length (including driven end disk ~0.8 mm)
P	=	Jump condition calculation for compaction pressure in Costantino's test
P_{wp}	=	Wetted perimeter in Kuo's paper
R	=	Intergranular stress used in Gough's formulation
R	=	Nondimensional porosity similarity parameter in Kuo's paper
T_i	=	Intragranular stress
U	=	Compaction front velocity in Costantino's test
U_p	=	Costantino's compressive wave speed
U_s	=	Costantino's shear wave speed
V_p	=	Velocity of Lexan piston just prior to bed impact in Costantino's test
Y	=	Empirical response surface of Gazonas' test matrix
a_1	=	Small disturbance propagation velocity
a	=	Wave speed used in the Gough's solid-phase wave equation
a,b,c,d,e,f	=	Correlation constants of Kuo's relations
b	=	Constant coefficients of the response surface in Gazonas' test
c	=	Wave speed
e_s	=	Internal energy of the solid phase
e_{so}	=	Initial internal energy of the solid phase
e_{ml}	=	Free energy of fusion above e_o
f	=	Interphase forces
Δt	=	Time between bed impact and detection of reaction in Costantino's test
u	=	Particle velocity of bed (piston velocity after bed impact) in Costantino's test
q	=	Order of the constitutive term of the response surface in Gazonas' test
$q_{o,1}$	=	Constants of the Robbins, Conroy viscoelastic model
x_i	=	Independent variable investigated in Gazonas' test
ε	=	Porosity
ε_o	=	Initial loading porosity
ξ	=	Inhomogeneous terms from Gough's derivation
ρ	=	Density

σ	=	Stress
τ_{wp}	=	Wall shear term in Kuo's paper
$\tau_{0,1,2}$	=	Empirical constants of Kooker and Anderson (1985) correlation
ϕ	=	Kuo's gas phase porosity
∇	=	Gradient
g	=	Subscript referring to the gas phase
s	=	Subscript referring to the solid phase

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